Direct Numerical Simulation of Aeolian Tones

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Abstract

Direct numerical simulation results of aeolian tones generated by a two-dimensional obstacle (circular cylinder, square cylinder, NACA0012 airfoil) in a uniform flow are presented and the generation and propagation mechanisms of the sound are discussed. The unsteady compressible Navier-Stokes equations are solved by a highly-accurate finite difference scheme over the entire region from near to far fields. The direct numerical simulation results are also compared with the results obtained by Curle's acoustic analogy.

Keyword: *Sound, Aeolian Tones, CAA, DNS*

1. Introduction

Aeolian tone is sound generated by an obstacle in a flow. Research of aeolian tone has a long history of more than one hundred years. Strouhal [1] experimentally found that the frequency f of the sound radiated from a cylinder of diameter D is related to the velocity U of a uniform flow as fD/U = const. The constant is now known as the Strouhal number, *St.* Since the work of Strouhal, a number of studies on aeolian tones have been made experimentally, theoretically and computationally. A brief survey for a circular cylinder has been given by Inoue and Hatakeyama [2].

Works in the field of computational aeroacoustics (CAA) can be categorized into three groups depending on the method to use: hybrid method, acoustic/viscous splitting method and direct numerical simulation (DNS) method. The first group (hybrid method) makes use of an acoustic analogy, under the assumption of a compact source, to predict the far-field sound. The source terms are evaluated using the near-field flow quantities, which are obtained by solving the incompressible Navier-Stokes equations for low-Mach-number flows. This method saves computational time as well as memory storage compared with DNS, because the flow in the far field is assumed to be stationary or uniform and thus not solved numerically. The second group (acoustic/viscous splitting method) assumes that flow quantities are represented, under the assumption of low Mach number, by an incompressible mean flow and a perturbation about the mean. In the far field, the perturbation quantities are equivalent to acoustic quantities. This method may possibly be a convenient method of predicting sound field resulting from low-Mach-number, non-compact source region. So far the results obtained by this method are qualitative, and detailed descriptions of sound fields have not yet been given. The third group makes use of DNS, where both the fluid motion and the sound which it generates are directly computed. Recent development of a high-performance supercomputer and highly-accurate numerical schemes makes it possible to simulate a sound field by directly solving the compressible Navier-Stokes equations over the entire region from near to far fields. This method does not suffer from restrictions such as low Mach number and compactness of the source region, but requires a large amount of computer resources; the studies using DNS are very few.

In this paper, DNS results of aeolian tones generated by a two-dimensional (2D) obstacle in a uniform flow are presented. One of the main purposes in this paper is to increase our understanding of the generation and propagation mechanisms of the sound. Special attention is paid to the relation among vortex shedding, forces acting on the obstacle and the nature of sound in the generation process. Special attention is also paid to the Doppler effect in the propagation process.

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2. Numerical Method

The 2D, unsteady, compressible Navier--Stokes equations were solved by a finite difference method. For spatial derivatives, a sixth-order-accurate compact Pade scheme (fourth-order-accurate at the boundaries) was adopted [3]. The fourth-order Runge--Kutta scheme was used for time-integration. The computational domain was divided into three subdomains; surface region close to the obstacle surface, sound region outside of the surface region, and buffer region. In the surface region, we used a fine grid spacing so that we can resolve the boundary layer on the obstacle surface. In the sound region, the grid spacing is larger than that in the surface region, but still small enough to capture sound pressure waves. In the buffer region, the grid spacing is large so that the pressure waves damp with increasing distance and become sufficiently weak before reaching the outer boundary of the computational domain. The grid spacings in the three regions were connected smoothly by a hyperbolic-tangent curve. Only the results obtained in the surface and sound regions were used for analysis.

Non-reflecting boundary conditions were used for the outer boundary of the computational domain [4]. The non-slip and adiabatic conditions were applied for obstacle surfaces. The Mach number, M, of the uniform flow was prescribed to be M = 0.05 to 0.3. The Reynolds number Re was prescribed to be Re =150 to 2000. For more details about the numerical method, readers are referred to Inoue and Hatakeyama [2] for a circular cylinder case.

3. Results

3.1. Generation and propagation mechanisms of sound

A typical example of computational results for the case of a circular cylinder is presented in Fig. 1, where an instantaneous vorticity and fluctuation pressure fields are shown. The Mach number is M = 0.2 and the Reynolds number based on the cylinder diameter and the velocity of the uniform flow is Re =150. In the vorticity field, “red” means that the sense of rotation of vortices is anticlockwise and “blue” means it is clockwise. The fluctuation pressure is defined as the deviation from the time-averaged pressure [2]. In the pressure field of Fig. 1, “red” means that the fluctuation pressure is positive and “blue” means it is negative.

Sound pressure pulses are generated in response to vortex shedding. When a vortex is shed from the upper side of the cylinder, a negative pressure pulse is generated on the upper side whereas a positive pressure pulse is generated on the lower side. On the other hand, when a vortex is shed from the lower side a negative pressure pulse is generated on the lower side whereas a positive pressure pulse is generated on the upper side. Therefore, alternate vortex shedding from the upper and lower sides of the cylinder produces positive and negative pressure pulses alternately on both sides of the cylinder; the generation frequency of pressure pulses is equal to the vortex shedding frequency and the

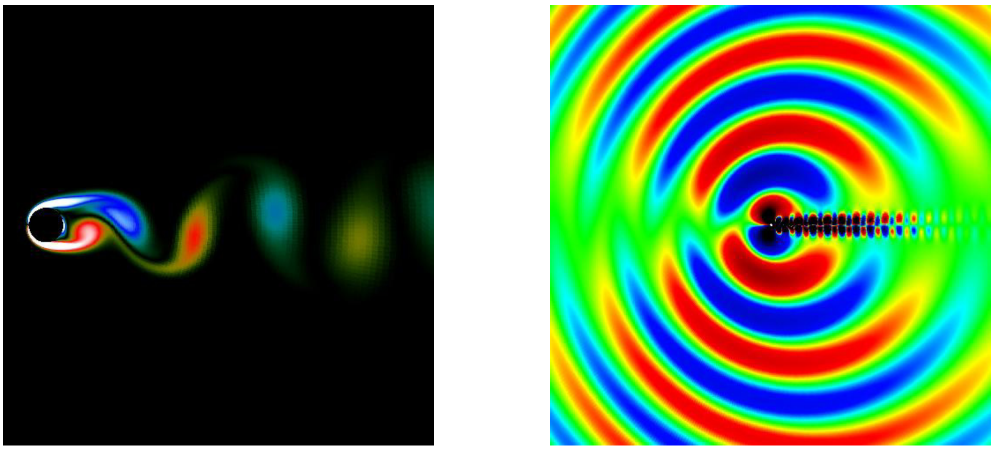

Fig. 1. Vorticity (left) and fluctuation pressure (right) fields. Circular cylinder. *M* = 0.2, *Re* = 150.

generated pressure pulses have a dipolar nature. As seen from Fig. 1, the generated pressure pulses propagate radially away from the cylinder with time. It should be noticed that the pressure pulses do not propagate normally to the flow direction, but propagate slightly upstream. This is because the cylinder is embedded in a uniform flow and thus the propagation of pressure pulses is affected by the Doppler effect.

An instantaneous vorticity and fluctuation pressure fields for the case of a square cylinder are presented in Fig. 2. The Mach number is M = 0.2 and the Reynolds number is Re =150. As we can see from Fig. 2, the generation and propagation mechanisms of pressure pulses are essentially the same as those in the circular cylinder case; sound pressure pulses are generated in response to vortex shedding and pressure pulses propagate upstream due to the Doppler effect. In this case, however, the amplitude of generated pressure pulses is smaller than that in the circular cylinder case, because the separation points of the flow are fixed and thus the fluctuation of the pressure is smaller in this case than that in the circular cylinder case.

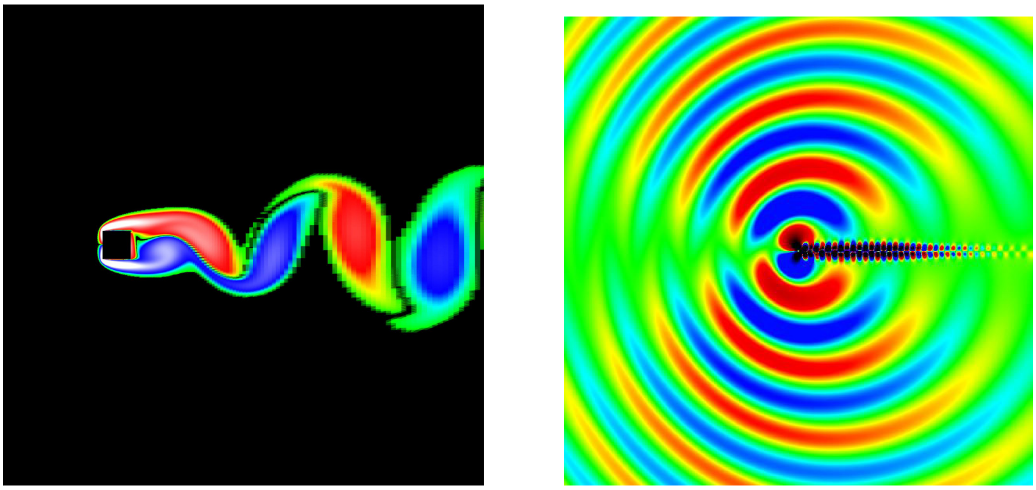

Fig.2. Vorticity (left) and fluctuation pressure (right) fields.
Square cylinder. M = 0.2, Re = 150.

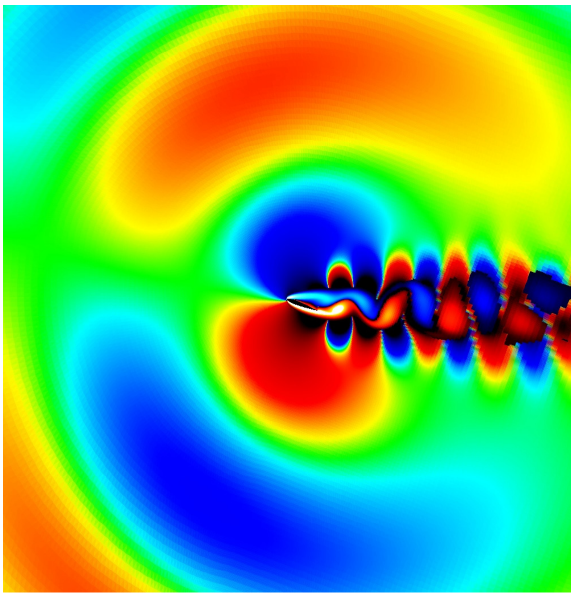

Fig. 3. Fluctuation pressure superimposed on vorticity. NACA0012. M = 0.2, Re = 300.

A typical example of computational results for the case of an NACA0012 airfoil is presented in Fig. 3, where an instantaneous fluctuation pressure field is superimposed on a vorticity field. The Mach number is M = 0.2 and the Reynolds number based on the airfoil chord length is Re =300. The angle of attack is 20 degrees. We can see from Fig. 3 that, in this case as well as in the circular and square cylinder cases, sound pressure pulses are generated in response to vortex shedding and that the generated sound has a dipolar nature. When a vortex is shed from the leading edge, a negative pressure pulse is generated on the upper side of the airfoil whereas a positive pressure pulse is generated on the lower side. On the other hand, when a vortex is shed from the trailing edge, a negative pressure pulse is generated on the lower side whereas a positive pressure pulse is generated on the upper side. Due to the asymmetric vortex shedding, that is, due to the difference between the strengths of the vortices shed from the leading edge and the trailing edge, the magnitudes of the generated pressure pulses are also different between the upper side and the lower side of the airfoil; the magnitude of the pressure pulses on the lower side is larger than that on the upper side. The propagation angle of the pressure pulses is dependent on the angle of attack and also different between the upper and lower planes of the airfoil; the pressure angle on the upper side is closer to 90 degrees and the pressure pulses on the lower side propagate more upstream than those in the circular cylinder case.

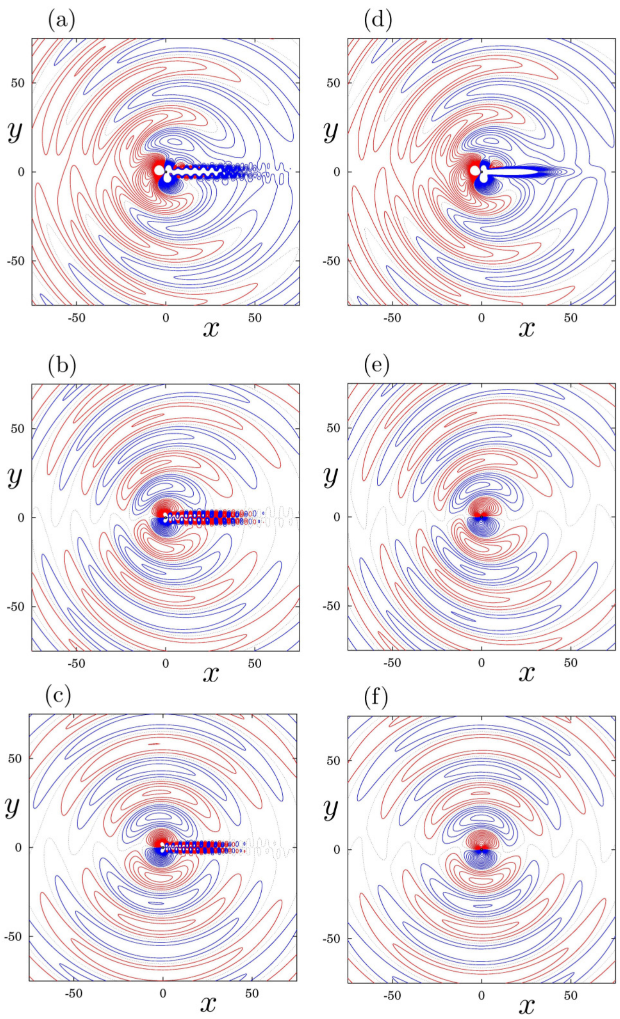

Fig. 4. Comparison between DNS and Curle's solutions. Circular cylinder. *M* = 0.2, *Re* = 150.
(a) Total pressure (DNS), (b) fluctuation pressure (DNS), (c) modified fluctuation pressure,
(d) sum of Curle's modified solution and mean pressure, (e) Curle's modified solution,
(e) Curle's solution.

3.2. Comparison with Curle's analogy

Shown in Fig. 4 is a comparison between DNS and Curle's solutions for the case of a circular cylinder [2]. The left-hand column shows the DNS results: (a) is the total pressure, (b) the fluctuation pressure and (c) is the modified fluctuation pressure in which the Doppler effect has been removed from the fluctuation pressure. The right-hand column shows the pressures obtained by Curle's acoustic analogy: (f) is Curle's solution, (e) is Curle's modified solution in which the Doppler effect is included, and (d) is Curle's modified solution superimposed on the mean pressure. It should be noted that the three pressures of the left-hand column are quite similar to those of the right-hand column: (a) is similar to (d), (b) to (e), and (c) to (f). This result indicates that the Curle's solution does not include either the Doppler effect or the mean pressure and that the Curle's solutions give a good approximation to the DNS results, if the Doppler effect and the mean pressure effect are taken into consideration.

4. Concluding Remarks

The generation and propagation mechanisms of the sound have been studied by direct numerical simulations for three different configurations of 2D obstacles (circular cylinder, square cylinder, and NACA0012 airfoil) which are immersed in a uniform flow of relatively low Reynolds numbers. In all the three cases, the sound pressure pulses are generated in response to vortex shedding. The generated pressure pulses propagate upstream due to the Doppler effect. The pressure pulses have a dipolar nature; lift dipole is dominant. The results showed that the magnitude of the generated pressure pulses are larger in the circular cylinder case than in the square cylinder case, because the separation points are fixed in the square cylinder case. The results for the case of NACA0012 airfoil showed that the magnitudes of the pressure pulses are different between the upper and lower planes because of the asymmetric vortex shedding.

From the results, we may say that DNS is a powerful tool to analyze acoustic fields at least for 2D, low Reynolds number flows. Direct numerical simulations of high Reynolds number flows and 3D flows past an obstacle of complex geometry are left for future works.

The results also showed that the Curle's solution may predict DNS results very well, though its applicability may be limited.

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